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MODEL OF FORMATION OF THE ELECTRIC CURRENT IN AIRCRAFT JET ENGINE DUCTS

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A possible mechanism of formation of electric currents ("engine currents") in aircraft engine jets (with subsequent charging of the aircraft) is investigated. This mechanism is a result of the presence of electrons and ions at concentrations of 10^7–10^{10} cm^{-3} in the gas flow in the engine duct. The electrons and ions are formed in the fuel combustion chamber as a result of chemo-ionization reactions. The wall flow zones in which the electrical quasi-neutrality of the medium is violated are considered. In these zones a nonzero normal component of the electric current is formed on the wall surface and a streamwise electric current develops in the duct. A general functional dependence of the engine current on the basic dimensionless parameters is obtained on the basis of similarity theory and dimensional analysis. Within the framework of electrical diffusion boundary layer theory a model problem of formation of the maximum possible engine current is formulated. A universal system of equations and boundary conditions, which contains no dimensionless parameters, is obtained and investigated. The engine current is qualitatively estimated for real engines and the calculation results are compared with the experimental data obtained under airfield conditions.

Aircraft charging as a result of jet engine operation (engine charging) has been investigated mainly under field conditions over several decades (see, for example, [1, 2]). It has been shown that this charging can be comparable with and even greater than the surface charging developed as a result of the flow past the aircraft. The main characteristic of engine charging is the electric engine current I, which is equal to the integral of the normal component of the electric current density over the outlet cross-section of the aircraft engine. The data obtained on the basis of airfield and flight experiments show that in the majority of cases the quantity I is a positive increasing function of the gas efflux velocity [2]. In the presence of the current I a charge Q whose sign is opposite to that of the total engine current is accumulated on the surface. This charge can be compensated by aircraft dischargers which are generally located in the aircraft wings. The dischargers emit charged particles opposite in sign to the particles responsible for the current I and release them into the surrounding space.

Under steady-state flight conditions the charging current is equal to the discharger current and on the aircraft surface a steady charge Q is concentrated. This charge depends on the quantity I and the characteristics of the dischargers. With increase in the "quality" of the latter the charge Q decreases. Thus, information on the current I is mainly necessary to make a correct choice of the characteristics of the dischargers, their number, and their location on the vehicle.

In recent years the problems of engine aircraft charging became especially topical in connection with the ecological problem of aircraft engine jets (physicochemical processes, condensation, generation of aviation aerosols, the effect on the ozone layer, etc.). Among the many publications concerning this problem we note studies [3–5] and the latest review [6]. The heterophase processes in the jets depend on the presence of charged components. The concentrations of the charged components are determined by the electro-physical conditions of gas flow through the engine which also shape the electric engine current. Therefore, the problems of aircraft charging and aviation ecology turn out to be interrelated. All this calls for a deeper analysis of the internal processes of engine charging.

The charged particles in engine jets can be ions and electrons formed as a result of chemo-ionization processes in the combustion chamber [7–9], charged carbon black particles, and charged particles formed as a result of mechanical damage to or partial disintegration of engine components [10]. Each of these possibilities requires an individual investigation.

In the present study one of the possible mechanisms of formation of an electric engine current in ducts is considered. This mechanism is associated with the presence of electrons and ions at the relatively low

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concentrations 10^7–10^{10} cm^{-3} characteristic of engine conditions and with the development of diffusion processes when the electric self-fields are taken into account.

Weakly ionized plasma duct flows (ambipolar diffusion, boundary layers, etc.) have been considered in numerous studies (see, for example, [11]). There have been many studies in which the engine current for various engines and energy systems is determined (for example, [2, 12, 13]). In the present study this experience is used to formulate model problems using which, together with similarity theory and dimensional analysis methods [14], the engine current formed in the duct is estimated.

1. GOVERNING EQUATIONS

In a duct located downstream of a weakly ionized gas source (combustion chamber) let there be zones with positive ions and electrons with identical concentrations ($n_i = n_e = n_0$). Directly in the chemo-ionization reaction zone (combustion chamber) the concentrations of the charged components reach 10^{10}–10^{11} cm^{-3} [7, 8]. In the duct the quantity n_0 will be by 1–2 orders lower than these values.

For the above concentrations of the components and in the absence of applied external electric fields the effect of the electric processes on the gas flow is certainly insignificant. The weakly ionized gas flow zones, which will be denoted by W, generally occupy only part of the duct. As a result of the convection and diffusion motion of the charged particles the zone W is deformed in the gas flow. The process of formation of an engine current starts only when the zone W contacts the duct walls or internal engine components (for example, the turbine blades).

Depending on the surface boundary conditions for the charged components, the electron and ion flows on the surfaces will be different and a nonzero net electric current normal to the surface develops. This leads to the onset of a nonzero longitudinal engine current in the duct. Against a background of gasdynamic boundary layers, diffusion boundary layers develop on the surfaces. These boundary layers generally consist of an outer zone, in which $n_e \approx n_i$, $\mathbf{j} = \mathbf{j}_e + \mathbf{j}_i = 0$ ($\mathbf{j}_e$, $\mathbf{j}_i$, and $\mathbf{j}$ are the vectors of the electron, ion, and total current densities), and an inner zone, in which $n_e \neq n_i$ and $\mathbf{j} \neq 0$.

In addition to the processes of convection and diffusion of charged particles and their drift in the electric self-field, it is generally necessary to consider the ion and electron recombination processes and the electron-neutral molecule adhesion with the formation of negative ions. Taking both these processes into account leads to a decrease in the engine current. However, as a result of the low electron and ion concentrations and the not-too-large duct lengths, in the first approximation particle recombination can be neglected. At high temperatures the process of adhesion of electrons to atoms is also not very intense [7]. Therefore, in what follows we will neglect electrochemical reactions. There will be additional justification for this if the aim of the investigation is to determine the maximum engine current.

In order to simplify the analysis we will also assume that both the electron and ion mobilities b_e and b_i and the diffusion coefficients D_e and D_i are constant (the inequalities $b_e \gg b_i$ and $D_e \gg D_i$ hold).

Under these assumptions the "electric" equations takes the form:

$$\operatorname{div} \mathbf{j}_e = 0, \quad \operatorname{div} \mathbf{j}_i = 0 \tag{1.1}$$

$$\mathbf{j}_e = -e\,[n_e(\mathbf{v} - b_e\mathbf{E}) - D_e \nabla n_e], \quad eD_e = kTb_e \tag{1.2}$$

$$\mathbf{j}_i = e\,[n_i(\mathbf{v} + b_i\mathbf{E}) - D_i \nabla n_i], \quad eD_i = kTb_i \tag{1.3}$$

$$\operatorname{div} \mathbf{E} = 4\pi e(n_i - n_e), \quad \mathbf{E} = -\nabla\varphi \tag{1.4}$$

Here, $\mathbf{E}$ is the electric field, φ is the electric potential, $\mathbf{v}$ is a given gas velocity distribution, T is the gas temperature (assumed to be constant), e is the electron charge, and k is Boltzmann's constant. In (1.2)–(1.3) the first expressions are Ohm's law for charged particles and the second are the Einstein relations. Expressions (1.1) and (1.4) are the continuity equations of the electron and ion components and the equation for determining the induced electric field.

Let us consider the boundary conditions. In the inlet duct cross-section the concentration distributions n_e and n_i must be specified. If these distributions are nonzero in the neighborhood of the duct wall, then downstream, depending on the boundary conditions on n_e and n_i, diffusion boundary layers develop on the walls. However,

if in the inlet duct cross-section n_e and n_i are nonzero only in the part far from the wall, then the charged particles can interact with the surfaces of various bodies mounted downstream in the duct.

In the outlet duct cross-section the boundary conditions for the concentrations must be formulated with allowance for the internal construction of the duct. In the numerical simulation, in several cases it is possible to specify "soft" boundary conditions in the outlet duct cross-section.

On the surface of the duct and bodies installed inside it we must specify the concentrations n_{ew} and n_{iw} (or more complex conditions involving the normal derivatives of the concentrations).

In order to determine the potential φ inside the duct we must generally specify its distributions on the boundary of the region: in the inlet and outlet cross-sections of the duct and on its internal surfaces. On the metal (conducting) sections of the surface the condition $\varphi = \text{const}$ must be satisfied and on the nonconducting sections we have the condition $j_n = 0$.

In the problem under consideration there is no external (applied) potential difference. The potential on the engine (and on the entire aircraft) arises as a result of charging. In the first approximation the potential can be assumed to be constant over the entire boundary of the region considered. With high-quality dischargers the potential becomes insignificant.

2. GENERAL EXPRESSION FOR THE ENGINE CURRENT

We will obtain a functional dependence for the streamwise engine current I in an arbitrary duct cross-section x. For the sake of simplicity, we will consider a plane duct with dimension z in the direction perpendicular to the flow plane. Since the violation of the quasi-neutrality of the medium and the onset of the current **j** take place in a narrow layer in the neighborhood of the surface whose thickness is much smaller than the transverse dimension of the duct, the latter dimension can be eliminated from the system of determining parameters, which will be denoted by S. In the case of a fairly long duct we can assume that the conditions in its outlet cross-section do not affect the electric processes inside the duct and, consequently, the duct length need not be included in S.

In accordance with Eqs. (1.1)–(1.4) and with allowance for the above remarks, the system S will include the determining parameters

$$x,\ u_0,\ n_0,\ en_{ew},\ en_{iw},\ D_e,\ D_i,\ kT/e \tag{2.1}$$

Here, u_0, n_0, n_{ew}, and n_{iw} are the characteristic velocity of the gas, the concentration of the charged particles in the initial cross-section, and their concentrations on the surfaces.

The system S also includes dimensionless parameters and constants contained in the dimensionless charged-particle concentration distributions in the initial cross-section and on the surfaces, in the gas velocity distribution, and in the functions describing the inner geometry of the duct.

Since the potential is determined correct to a constant, if a constant and identical value φ_w is assigned over the entire boundary of the region, the quantity φ_w will likewise not enter into the system S.

Using similarity theory and dimensional analysis [14], on the basis of (1.5) we obtain

$$I = e n_0 r_d u_0 z f\left(\frac{x}{r_d},\ \frac{n_{ew}}{n_0},\ \frac{n_{iw}}{n_0},\ \frac{D_e}{u_0 r_d},\ \frac{D_i}{u_0 r_d}\right), \qquad r_d^2 = \frac{kT}{4\pi e^2 n_0} \tag{2.2}$$

The function f also contains the above-mentioned additional set of dimensionless parameters and constants. The engine current corresponds to $x = L$, where L is the duct length.

The quantity r_d is the Debye shielding radius. The quantities en_0 and $r_d z$ are the characteristic values of the volume electric charge density and the volume in which the charge is concentrated. The dimensional multiplier of the function f represents the characteristic convective axial current.

The last two parameters in (2.2) are the ratios of the electron and ion diffusion rates in the Debye layer to the gasdynamic velocity. We will estimate their values under the following gasdynamic conditions: $u_0 = 100$ m/s, $T = 100$ K, and $p = 6.09$ atm. H_3O^+ ions are mainly formed in fuel combustion chambers [7, 8]. At $T = 300$ K and $p = 1$ atm the diffusion coefficient of these ions in air is equal to $7.71 \cdot 10^{-2}$ cm^2/s [15]. Since the relation $D_i \sim T^{3/2}/p$ is satisfied, this value of the ion diffusion coefficient turns out to be also valid for the initial values of T and p. The quantity D_e can be found using the estimate $D_e/D_i = 10^3$. These values of the parameters are given in Table 1,

Table 1

n_0, cm^{-3}	r_d, cm	$en_0u_0r_d$, μA/cm	D_i/u_0r_d	D_e/u_0r_d	$u_0^2r_d/D_e$, cm	E_d=4πen_0r_d, V/cm	$m=u_0/b_eE_d$
10^7	0.069	$1.1{\cdot}10^{-3}$	$1.12{\cdot}10^{-4}$	0.112	0.62	1.25	8.95
10^8	0.022	$3.47{\cdot}10^{-3}$	$0.35{\cdot}10^{-3}$	0.35	0.062	3.94	2.83
10^9	0.0069	0.011	$1.12{\cdot}10^{-3}$	1.12	0.0062	12.5	0.895
10^{10}	0.0022	0.0347	$0.35{\cdot}10^{-2}$	3.5	0.00062	39.4	0.283

from which it follows that $D_i/u_0r_d \ll 1$. Thus, this parameter can be eliminated from the arguments of the function f (if this function is analytic in this parameter).

We will consider the situation in which the current I is maximal. For this purpose we will assume that in the charged layer the ion component is "frozen" into the gasdynamic flow ($D_i=b_i=0$) and the surface is ideally catalytic for the electron component ($n_{ew}=0$). In this case the second and third arguments can be eliminated from the function f and from (2.2) we obtain the expression

$$I=en_0r_du_0z\,f(x/r_d,\ D_e/(u_0r_d)) \tag{2.3}$$

3. EQUATIONS FOR THE QUASI-NEUTRAL ZONE

The medium is quasi-neutral outside the Debye layer. The corresponding equations can be obtained in the usual way. We set $n_i=n_e=n$, the first and second equations of (1.1) are multiplied by b_i and b_e, respectively, and summed (with allowance for (1.2) and (1.3)), and then the first and second equations of (1.1) are subtracted from one another. As a result, we obtain the relations

$$\operatorname{div}(D_a\nabla n - n\mathbf{v})=0, \qquad D_a=\frac{D_eb_i + D_ib_e}{b_e + b_i} \tag{3.1}$$

$$\operatorname{div}(\chi\nabla n + n\mathbf{E})=0, \qquad \chi=\frac{D_e - D_i}{b_e + b_i} \tag{3.2}$$

Here, D_a is the ambipolar diffusion coefficient. The elliptic diffusion equation (3.1) serves to determine the concentration n, and equation (3.2) to determine $\mathbf{E}$. A possible solution of this equation is the relation

$$\mathbf{E}=-\chi\nabla\ln n \tag{3.3}$$

When (3.3) is satisfied, the currents $\mathbf{j}_e$ and $\mathbf{j}_i$ can be determined from the formulas

$$\mathbf{j}_e=e(D_a\nabla n - n\mathbf{v}), \qquad \mathbf{j}_e + \mathbf{j}_i=\mathbf{j}=0 \tag{3.4}$$

Situations in which equation (3.1) and expression (3.3) give a solution of the entire problem are possible. For example, let us consider the diffusion of charged particles in a duct when the electric potential of its walls and the inlet and outlet cross-sections is constant and equal, in the inlet cross-section the electron and ion concentrations satisfy the condition $n_i=n_e=n_0=\text{const}$ and on the walls the conditions $n_i=n_e=n_0=\text{const}$ are fulfilled. In the outlet cross-section soft boundary conditions are specified. These conditions make it possible to determine the concentration n in the entire channel up to its walls using Eqs. (3.1). The electric field determined from the solution (3.3) must satisfy the boundary condition $E_s=-(\chi\partial n/\partial s)_n=0$ on the boundary of the region. Over the entire flow the medium is quasi-neutral and the function f in (2.2) is equal to zero.

If $n_i\neq n_e$ on the boundary of the region or if after the determination of n, using (3.1) the solution will not satisfy the electric boundary conditions, then in the neighborhood of the wall a charged layer in which $\mathbf{j}\neq 0$ develops and a streamwise electric current appears. We will estimate the electric fields $E^{(e)}$ and $E^{(i)}$ in the quasi-neutral and near-wall regions, respectively. Using (3.3), we obtain $E^{(e)}\sim\chi/\delta\sim D_e/b_e\delta=kT/e\delta$, where δ is the characteristic thickness of the diffusion layer. Setting $n_i - n_e\sim n_0\neq 0$, from the first of equations (1.4) we obtain $E^{(i)}\sim E_d=4\pi en_0r_d$, where the Debye radius r_d is given in (2.2). The external and internal electric field ratio is equal to r_d/δ in order of magnitude. Characteristic values of the field E_d are given in Table 1.

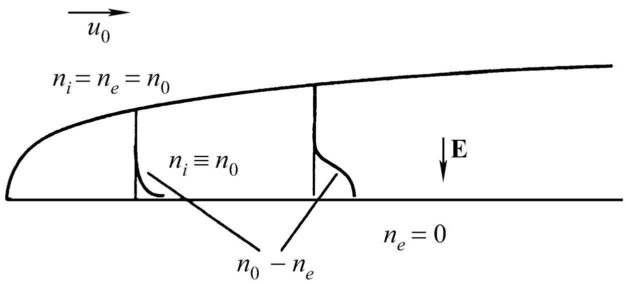

Fig. 1. Diagram of the flow in an electric diffusion boundary layer.

4. STANDARD PROBLEM FOR ESTIMATING THE ENGINE CURRENT

We will now consider in more detail the situation for which the functional relation (2.3) was obtained. Let a gas with uniform thermodynamic parameters move with uniform velocity $\mathbf{v} = (u_0, 0, 0)$ in a plane duct of constant cross-section. In the inlet cross-section we specify uniform distributions of the charged component: $n_i = n_e = n_0$. The ions are assumed to be frozen into the medium, so that over the entire space $n_i \equiv n_0$. The wall surface is assumed to be ideally catalytic with respect to electrons ($n_{ew} = 0$). In the input and output duct cross-sections and on the walls the potential φ is assumed to be equal to zero. By virtue of the symmetry of the problem $E_y = 0$ on the duct axis.

The engine current is formed in a wall layer whose thickness should not much exceed the Debye radius r_d. Here the electron concentration decreases toward the wall and a positive electric charge is concentrated in the layer. This charge is entrained from the duct by convection in the longitudinal direction x. Assuming that the characteristic scales of variations of the electric field in the transverse and longitudinal directions are equal to r_d and L, where $\varepsilon = r_d/L \ll 1$, and using the equation $\operatorname{curl}\mathbf{E} = 0$, we obtain the estimate

$$E_x = \int_0^y \frac{\partial E_y}{\partial x}\, dy \sim E_y \varepsilon \tag{4.1}$$

Using (4.1), we obtain

$$\frac{\partial n_e E_y}{\partial y} \sim \frac{n_0 E_y}{r_d}, \qquad \frac{\partial n_e E_x}{\partial x} \sim \frac{n_0 E_y \varepsilon}{L}, \qquad \frac{\partial n E_x}{\partial x} \sim \varepsilon^2 \frac{\partial n E_y}{\partial y}$$

$$\frac{\partial E_x}{\partial x} \sim \varepsilon^2 \frac{\partial E_y}{\partial y}, \qquad \frac{\partial^2 n_e}{\partial x^2} \sim \varepsilon^2 \frac{\partial^2 n_e}{\partial y^2}, \qquad \mathbf{E} = (E_x, E_y, 0)$$

In these estimates we used characteristic values of the corresponding quantities and their derivatives. With allowance for the above assumptions and estimates, from the general system of equations (1.1)–(1.4) we obtain the following equations of the electric diffusion boundary layer

$$u_0 \frac{\partial n_e}{\partial x} - b_e \frac{\partial E n_e}{\partial y} = D_e \frac{\partial^2 n_e}{\partial y^2}, \qquad D_e = \frac{kT}{e} b_e$$

$$\partial E/\partial y = 4\pi e(n_0 - n_e), \quad E \equiv E_y, \quad x = 0, \quad y > 0: \quad n_e = n_0, \quad E = 0 \tag{4.2}$$

$$x > 0, \qquad y = 0: \qquad n_e = 0; \qquad y = \infty: \qquad n_e = n_0, \qquad E = 0 \tag{4.3}$$

In Fig. 1 we have reproduced the corresponding flow scheme.

In (4.2) and (4.3) we now go over to dimensionless variables, using the formulas

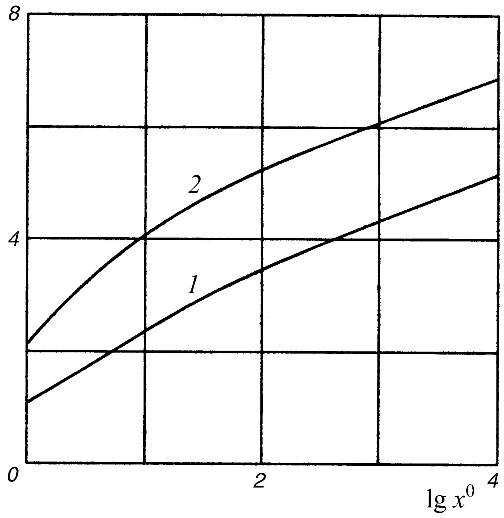

Fig. 2. Dimensionless current (curve *1*) and dimensionless thickness of the electric boundary layer determined on the basis of the concentration $n^0 = 0.9$ (curve *2*) as functions of the dimensionless longitudinal coordinate.

$$x = r_d m x^0, \quad y = r_d y^0, \quad n_e = n_0 n^0, \quad E = E_d E^0, \quad m = u_0/b_e E_d, \quad E_d = 4\pi e n_0 r_d \tag{4.4}$$

$$\partial n^0/\partial x^0 - \partial E^0 n^0/\partial y^0 = \partial^2 n^0/\partial y^{02}, \qquad \partial E^0/\partial y^0 = 1 - n^0 \tag{4.5}$$

$$\begin{gathered} x^0 = 0, \quad y^0 > 0: \quad n^0 = 1, \quad E^0 = 0 \\ x^0 > 0, \quad y^0 = 0: \quad n^0 = 0; \quad y = \infty: \quad n^0 = 1, \quad E^0 = 0 \end{gathered} \tag{4.6}$$

It is significant that the equations and boundary conditions (4.5) do not contain dimensionless parameters, i.e., this system is universal.

We will derive an expression for the engine current I in the duct cross-section x. Taking into account the fact that in the approximation considered the longitudinal electric field and the derivatives of n_e with respect to x are not taken into account, we obtain

$$\begin{gathered} I = z\int_0^\infty e(n_0 - n_e) u_0 \, dy = e n_0 r_d u_0 z f(x^0) \\ f(x^0) = \int_0^\infty (1 - n^0)\, dy^0, \qquad x^0 = (x D_e)/(u_0 r_d^2) \end{gathered} \tag{4.7}$$

Thus, f in formulas (2.3) depends only on a single variable x^0 which represents the product of the arguments x/r_d and $D_e/u_0 r_d$. Using the second equation for E^0, we obtain

$$f(x^0) = -E_w^0, \qquad I = -z u_0 \sigma, \qquad E_w = 4\pi\sigma \tag{4.8}$$

Here, $\sigma = \sigma(x)$ is the surface charge on the ideally conducting wall and E_w is the value of E_y on the wall. In this case $E_w < 0$ and $\sigma < 0$.

We will determine the behavior of $f(x^0)$ as $x^0 \to 0$. In a small neighborhood of this point we can neglect the electron drift and the concentration distributions n^0 are described by the classical diffusion equation $\partial n^0/\partial x^0 = \partial^2 n^0/\partial y^{02}$ with boundary conditions (4.6). Its solution has the form:

$$f(x^0) = 2\sqrt{x^0/\pi}\,, \qquad I = e n_0 u_0 z \sqrt{(4 x D_e)/(\pi u_0)} \tag{4.9}$$

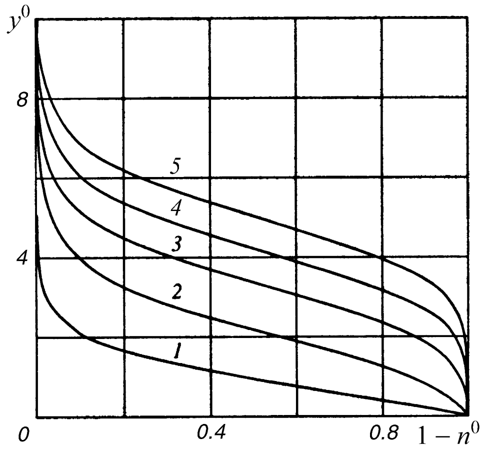

Fig. 3

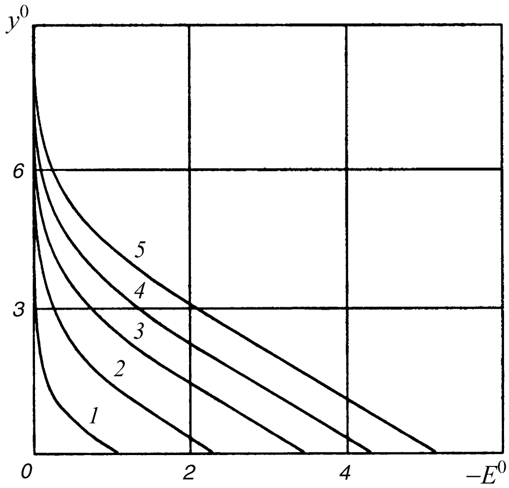

Fig. 4

Fig. 3. Profiles of the dimensionless volume electric charge density (the quantities $1 - n^0$) in the cross-sections $x^0 = 1$, 10, 100, 1000, 10000 (curves *1–5*, respectively).

Fig. 4. Profiles of the dimensionless electric field in the same cross-sections as in Fig. 3.

Table 2

n_0, cm^{-3}	$r_d m$, cm	$r_d m \cdot 40$, cm	$r_d m \cdot 10^3$, cm	$x^0 = 10/r_d m$
10^7	0.62	25	620	16
10^8	0.062	2.5	62	160
10^9	$6.2 \cdot 10^{-3}$	0.25	6.2	1600
10^{10}	$6.2 \cdot 10^{-4}$	0.025	0.62	16 000

$$n^0 = \Phi(\eta), \qquad \Phi(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta e^{-\eta^2} d\eta, \qquad \eta = y^0 / 2\sqrt{x^0} \tag{4.10}$$

The presence of the induced electric field and, accordingly, electric electron drift reduces the engine current determined from formula (4.10) and calculated with allowance for only electron diffusion and convection.

We will give the results of numerically integrating Eqs. (4.5)–(4.6). In Fig. 2 we have reproduced the dependence of the boundary layer thickness on the longitudinal coordinate and the function $f(x^0)$. For $x^0 > 50$ this function can be fairly correctly approximated by the dependence $f \approx 0.85 \lg x^0 + 1.8$.

In Figs. 3 and 4 we have reproduced the development of the profiles of the electric charge density $1 - n^0$ and the electric field E^0 in the boundary layer, respectively.

Using the standard problem as an example, we can determine the engine current of an engine element. Let this element be an annular duct of length 10 cm consisting of N subducts formed by N surfaces (for example, by thin blades of the working section). In Fig. 5 we have plotted the cross-section of this channel. Electric boundary layers develop on the cylindrical surfaces of the annular duct and on the both sides of each of the N surfaces. The dimension z is given by the expression $z = 2\pi(R_1 + R_2) + 2(R_2 - R_1)N$. In accordance with formula (4.7) and the data of Table 2, the dimensionless lengths of the annular duct x^0 are equal to 160 and 1600 for $n_0 = 10^8$ and 10^9 cm^{-3}. From Fig. 2 it follows that in this case $f(x^0) \approx 3.6$ and 4.5. The corresponding values of the complex $i = en_0 r_d u_0$ are given in Table 1.

Let $R_1 = 50$ cm, $R_2 = 60$ cm, and $N = 30$. In this case $z = 1291$ cm and the engine current formed on the length $L = 10$ cm is equal to 16.3 μA for $n_0 = 10^8$ cm^{-3} and 63.9 μA for $n_0 = 10^9$ cm^{-3}.

It is important to note that further increase in the length L leads to only a slight increase in the current I.

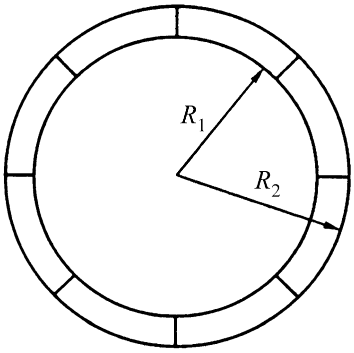

Fig. 5. Diagram of an annular aircraft engine duct.

This is associated with the weak (nearby logarithmic) asymptotics of the function f as $x^0 \to 0$.

These values of the engine current correspond to the data of airfield experiments [2].

Summary. A possible mechanism of formation of the electric engine current emitted from an aircraft jet engine, based on the presence of electron and ion components in the engine duct and the development of diffusion electric processes on the inner surfaces of the engine and on the surfaces of its inner elements, is considered. The concentration of the electrons and ions formed in the engine combustion chamber as a result of chemo-ionization reactions is too small to affect the gasdynamic flow but quite sufficient to form an electric engine current.

A functional expression for the engine current is obtained on the basis of similarity theory and dimensional analysis. When the ion component is "frozen" into the gasdynamic flow, the surface is ideally catalytic for electrons and the gas velocity is uniform, a universal system of equations and boundary conditions which contains no dimensionless parameters is obtained. This system is analyzed theoretically and numerically and on the basis of this analysis the engine current is estimated for a real aircraft engine. The estimate obtained agrees with the airfield and flight experimental data.

The theory developed reproduces the basic features of the experimental data on aircraft engine currents: in accordance with the theory, the engine current is positive and increases with the gas efflux velocity.

REFERENCES

1. I. M. Imyanitov, *Aircraft Charging in Clouds and Precipitation* [in Russian], Gidrometeoizdat, Leningrad (1970).
2. A. B. Vatazhin, V. I. Grabovskii, V. A. Likhter, and V. I. Shul'gin, *Electrogasdynamic Flows* [in Russian], Nauka, Moscow (1983).
3. A. B. Vatazhin and A. A. Sorokin, "Aircraft atmospheric aerosols and ecological problems," *Izv. Ros. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 6, 57 (1992).
4. A. B. Vatazhin (Ed.) *Turbulent Jet Flows with Condensational and Electrophysical Effects* [in Russian], *Tr. TsIAM*, No. 1288 (1991).
5. A. Vatazhin, A. Lebedev, V. Likhter, V. Shulgin, and A. Sorokin, "Turbulent air-steam jets with a condensed dispersed phase: Theory, experiment, numerical modeling," *J. Aerosol. Sci.*, **26**, 71 (1995).
6. O. B. Popovicheva, A. M. Starik, and O. N. Favorskii, *Effect of Aviation on the Atmosphere. Research Problems and Prospects,* Preprint No. 8–427 [in Russian], United High-Temperature Institute of the RAS, Moscow (1998).
7. J. Lawton and F. J. Weiberg, *Electrical Aspects of Combustion,* Clarendon Press, London (1969).
8. K. E. Ulybyshev, "Electric structure of the combustion front in a homogeneous methane-air mixture," *Izv. Ros. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 1, 3 (1998).
9. N. I. Kidin and G. M. Makhviladze, "Electric field of a laminar flame with a high degree of ionization," *Fiz. Gor. Vzryv.*, **12**, 865 (1976).
10. A. B. Vatazhin, D. A. Golentsov, V. A. Likhter, and V. I. Shul'gin, "Electrical aspects of body disintegration in a gasdynamic flow," *Izv. Ros. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 4, 74 (1999).
11. G. W. Sutton and A. Sherman, *Engineering Magnetohydrodynamics*, McGraw-Hill, New York (1965).
12. L. T. Chernyi, "Charging of particles of a suspension in collisions with boundary surfaces. Limiting case: ideally conducting and nonconducting particles," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza,* No. 4, 80 (1980).
13. V. N. Pribylov, "Charging of walls of a plane duct by an aerosol flow containing solid charged particles," *Vestn. MGU, Ser. Matematika, Mekhanika,* No. 5, 37 (1997).
14. L. I. Sedov, *Similarity and Dimensional Methods in Mechanics,* Acad. Press, New York (1959).
15. I. S. Grigor'ev and E. Z. Meilikhov (Eds.), *Physical Quantities. Handbook* [in Russian], Energoatomizdat, Moscow (1991).